

PHASE I NAVSTAR/GPS EPHEMERIS  
AND SPACE VEHICLE CLOCK PERFORMANCE SUMMARY

Albert B. Bierman  
The Aerospace Corporation

ABSTRACT

The Navstar/Global Positioning System (GPS) has been under evaluation for more than one year. This paper, one of several Major Field Test Objective reports, addresses the issue of Control Segment accuracy in predicting Space Vehicle (SV) clock and ephemeris states for broadcast to the user community. Both the highly precise ephemeris and clock prediction data blocks and the less precise (but longer period of utility) almanac data block are evaluated.

## 1. INTRODUCTION

The Navstar/Global Positioning System (GPS) is a satellite-based navigation system that provides extremely accurate three-dimensional position, velocity and time information to properly equipped users anywhere on or near the earth. It is a Joint Service Program, managed by the Air Force with deputies from the Navy, Army, Marines, Defense Mapping Agency, Coast Guard and NATO with technical support provided by The Aerospace Corporation.

Phase I - Concept Validation - has been undergoing test and evaluation in preparation for the second stage of the Defense Systems Acquisition Review Council (DSARC-2) in Spring 1979. An extensive flight test program has been conducted at the Yuma Proving Ground in Arizona and, to a lesser extent, off the coast of Southern California and at other sites in the continental United States.

While the ultimate objective is to demonstrate precision navigation for a wide range of military missions, it is equally important to verify the performance of all aspects of the GPS system. To accomplish these goals a series of papers has been prepared to support major field test objectives for DSARC-2.

### 1.1 OBJECTIVES

This paper addresses the accuracy of the ephemeris and space vehicle (SV) clock predictions which are vital to the user navigation function. The Phase I system specification (Ref.1) allocates 3.66 meters (1 sigma) for the ephemeris error

contribution to the User Equivalent Range Error during the twenty-four hour period after the satellite upload message has been prepared. Phase I satellites have rubidium frequency references as atomic standards. The GPS error budget allocates 2.74 meters (1 sigma) for the SV clock error during the two hour period after the satellite upload message has been generated. The Phase I clock error is predicated on a rubidium atomic standard with fractional frequency stability of 1 part in  $10^{12}$  over a two hour period. Operational satellite clocks will be cesium beam tube or hydrogen maser standards. These clocks offer frequency stability of 1 part in  $10^{13}$  or better over 24 hours. Thus the Phase III Operational GPS can be expected to provide better than 3 meters (1 sigma) accuracy over the twenty-four hour period after the navigation message has been prepared.

## 1.2 SCOPE

This assessment will evaluate (1) the ephemeris and SV clock error contributions to user ranging error (URE) during the two-hour periods following navigation data uploads; (2) the error contributions throughout the twenty-four hour period following navigation data uploads; and (3) SV almanac data accuracy for 2 weeks or more after upload. It is important to note that while item (2) addresses twenty-four hour accuracy, there is no prescribed Phase I clock error budget beyond two hours.

The adequacy of item (3) will be judged against the almanac URE (1 sigma) values (Ref. 2) presented in Table I.

Table I. Almanac Accuracy

Time	User Equivalent Range Error estimated by analysis (meters)
1 day	1000
1 week	2500
2 weeks	5000
3 weeks	10000
4 weeks	15000
5 weeks	20000

## 2. SYSTEM DESCRIPTION

GPS is comprised of three system components (1) the Space Segment, (2) the User Segment, and (3) the Control Segment.

### 2.1 SPACE SEGMENT

The Space Segment provides the spaceborne navigation payload. Phase I uses four space vehicles in 10,900 nmi (20,200 km) altitude circular orbits inclined 63 degrees with respect to the equator. The satellites are distributed in two inertial planes which provide an hour or more of usable four Space Vehicle (SV) geometry for daily user testing at the Yuma Proving Ground (YPG). Table 2 presents a summary of the constellation configuration. The orbit periods are controlled to cause the ground traces to repeat each day. Fig. 1 illustrates the repeating satellite geometries. Because of the sidereal effect of the earth's motion about the sun, and orbit torques by the oblate earth and by sun-moon effects, each day's events occur approximately 4 minutes and 3.4 sec earlier than the previous day's events. Satellite geometry at the YPG is described by the azimuth-elevation time history in Figure 2. The satellite positions at 1 January 1979/1700 GMT are shown on Figs. 1 and 2. At that time, the opportunity for four satellite navigation at YPG was nearing termination due to the fade of Navstar 4.

The major elements comprising the navigation payload are the pseudo random noise sub assembly (PRNSA), atomic frequency standard, processor, and L-band antenna. The PRNSA includes the baseband generator, which produces the P (precise) and C/A (coarse/acquisition) ranging codes and encodes navigation data from the processor onto the pseudo random noise (PRN)

Table II. Navstar Phase I Orbits at First  
Ascending Node on 1 Jan. 1979

SATELLITE IDENTIFIER	NODAL PERIOD, min	INCLINATION, deg	LONGITUDE OF FIRST ASCENDING NODE, deg	RIGHT ASCENSION OF ASCENDING NODE (1), deg	TIME OF FIRST ASCENDING NODE, GMT	ECCENTRICITY	ARGUMENT OF PERIGEE, deg	DATE OF LAUNCH
NS-1	717.982	63.12	46.12	218.06	0448:18	0.0034	345.5	21 FEB 1978
NS-2	717.983	63.41	331.61	100.25	0155:30	0.0051	93.4	12 MAY 1978
NS-3	717.985	63.03	352.81	98.15	0022:18	0.0015	350.4	7 OCT 1978
NS-4 <sup>(2)</sup>	717.988	63.13	95.71	217.67	0033:48	0.0008	77.4	10 DEC 1978

(1) Referenced to astronomical coordinates of 1950.0

(2) Data for 15 January 1979

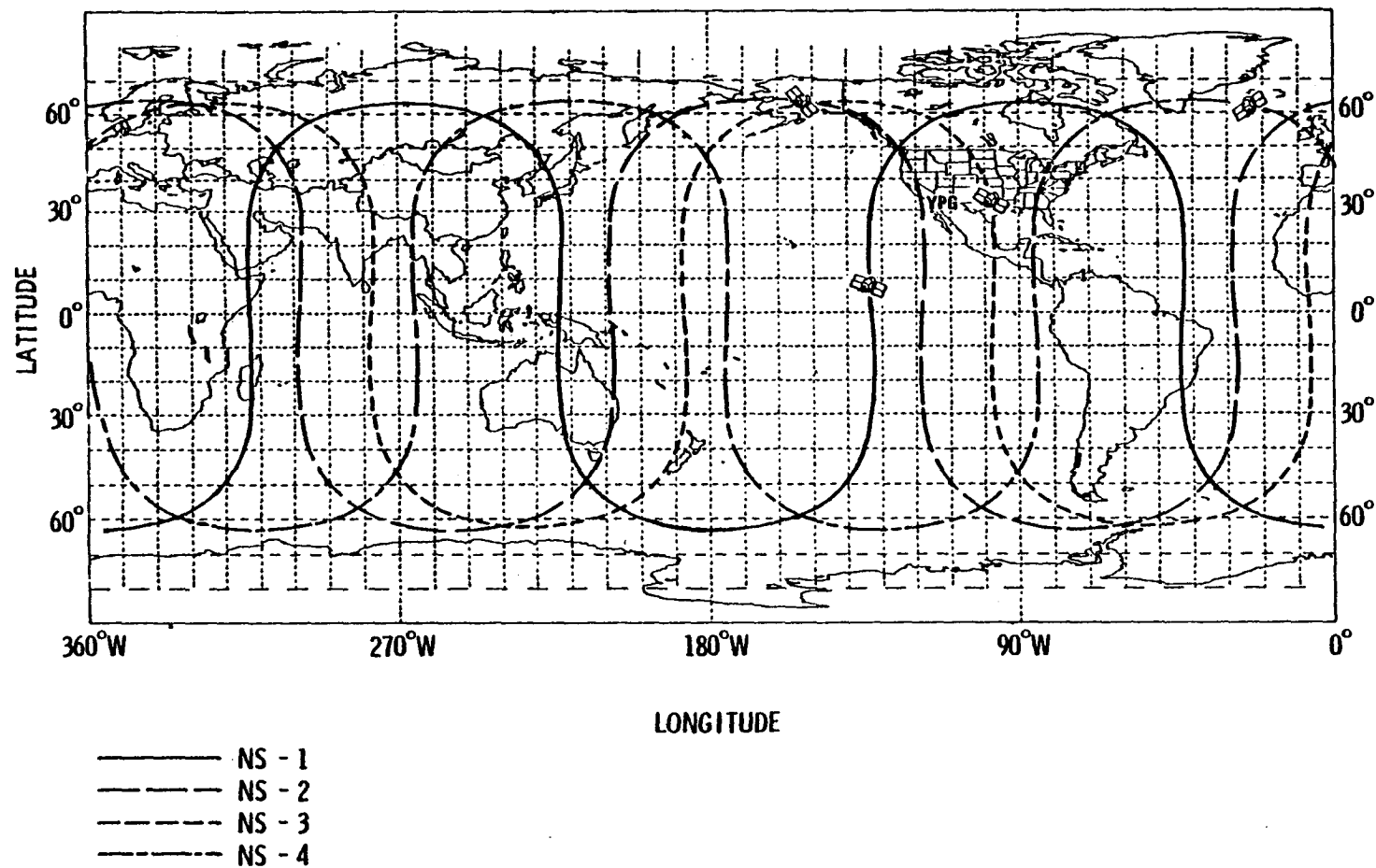
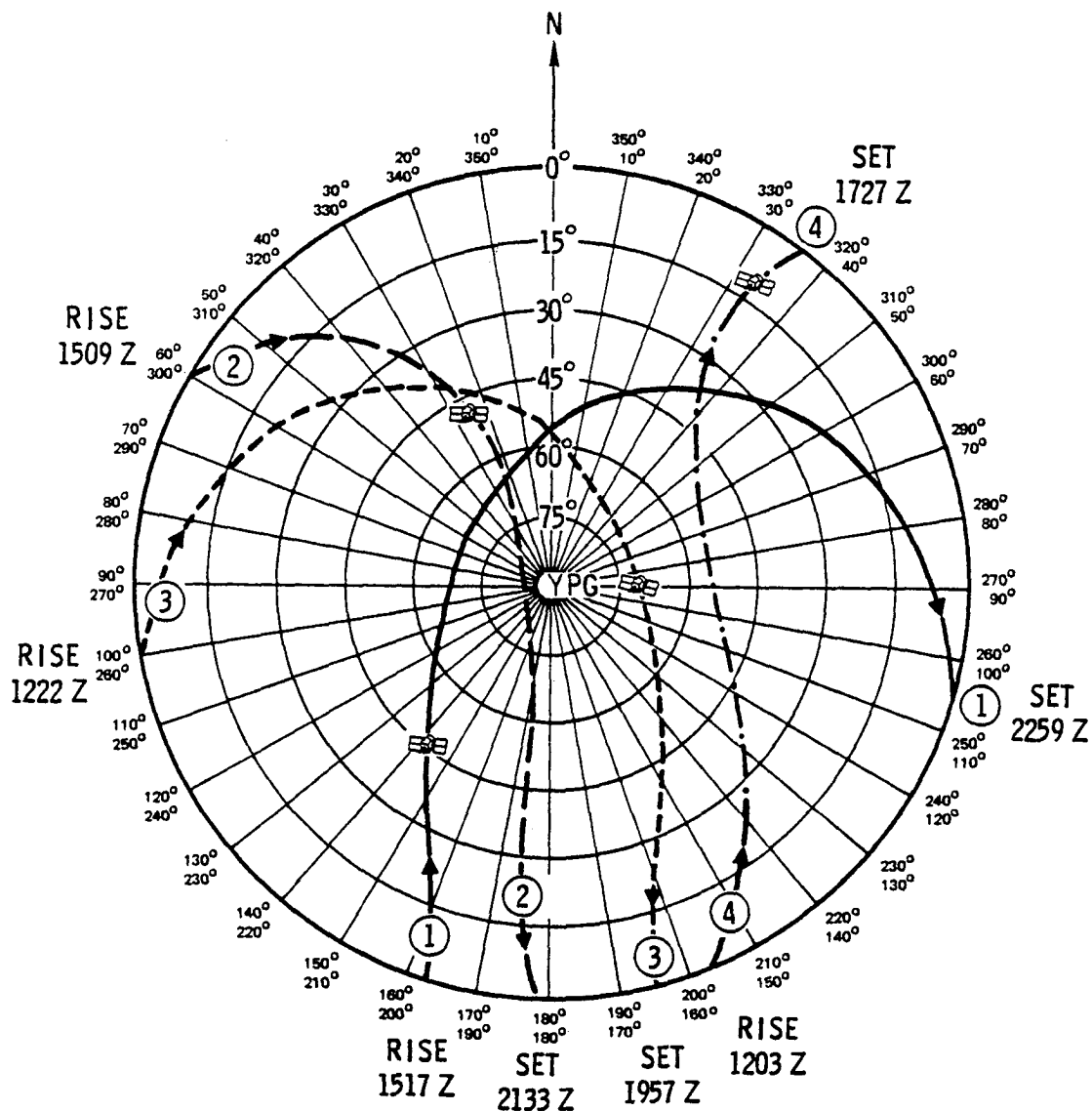


Figure 1. Ground Traces of the Phase I Constellation



- NOTE:
1. TIMES SHOWN ARE GREENWICH MEAN TIME
  2. SATELLITE LOCATIONS INDICATE POSITIONS AT 1700Z ON 1 JAN 1979
  3. RISE = SATELLITE APPEARANCE ABOVE HORIZON  
SET = SATELLITE DISAPPEARANCE BELOW HORIZON

Figure 2. Satellite Geometries at the Yuma Proving Ground



ranging signal; the amplifier/modulator units that supply the  $L_1$  (1575.42 MHz) and  $L_2$  (1227.6 MHz) carrier frequencies modulated by the PRN ranging signals; and the high-power amplifiers that amplify the carrier signals for transmission.

## 2.2 USER SEGMENT

The User Segment consists, in part, of navigation avionics which measure pseudo range and delta (pseudo) range using the navigation signal from each satellite. Pseudo range is the true distance from the satellite transmitter to the user antenna phase center plus an offset due to the user's clock bias. Similarly, delta range is the incremental range change over a specified time interval plus an offset due to the user's frequency bias. Each signal carries ephemeris data and system timing information modulated at 50 bps. The low data rate information forms the navigation message, which permits the user receiver/processor to convert pseudo range and delta range measurements to user three-dimensional position and velocity.

Navigation message data consists of five subframes each containing 300 bits of data (Fig. 3). Subframe 1

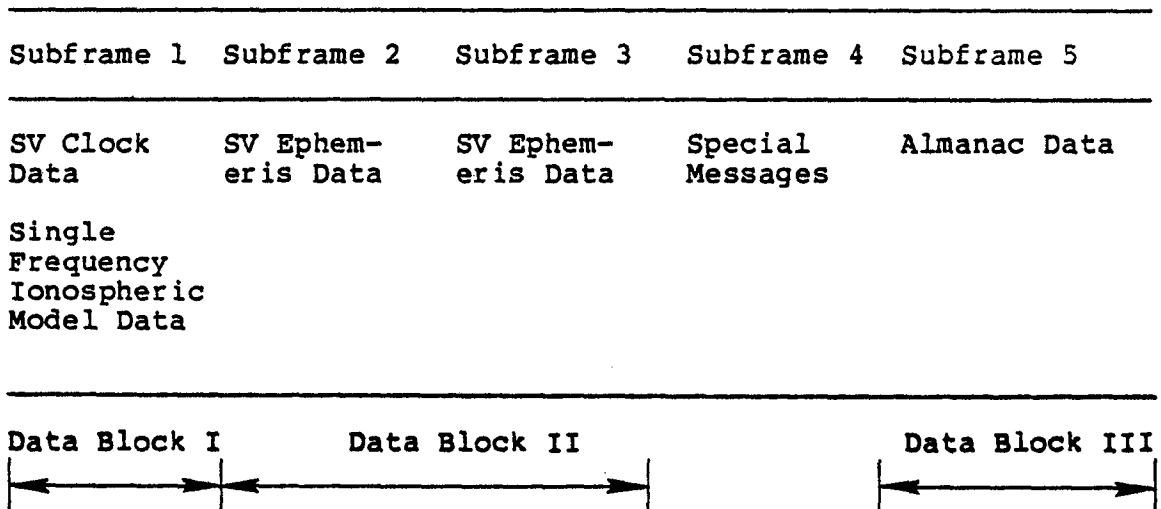


Figure 3. Navigation Message Structure

contains data to establish system time and a set of coefficients with which a single frequency user can model the signal delay due to the ionosphere. The data in subframe 1 is also referred to as data block I. Subframes 2 and 3 contain data from which the satellite position and velocity can accurately be determined. These two subframes are referred to as data block II. Subframe 4 contains alpha numeric data irrelevant to navigation. Subframe 5 provides data similar to data block II but of reduced accuracy. Every thirty seconds the almanac of a different satellite appears in data block III.

### 2.3 CONTROL SEGMENT

The Control Segment consists of a Master Control Station (MCS), an Upload Station (ULS), and monitor stations (MS) located in Hawaii, Guam, Alaska, and at Vandenberg AFB, California. The monitor stations passively track all satellites in view and accumulate pseudo ranging data, which is transmitted to the MCS where it is processed to provide estimates of the satellite ephemerides and clock offsets. At least once a day these estimates are extrapolated forward in time to provide predictions of the SV ephemeris and clock states. These predictions are the basis of the new navigation message that is transmitted by the upload station to the satellites for subsequent downlink transmission encoded on the carrier signals. The MCS, ULS, and the Vandenberg monitor station are co-located.

As previously described, the satellite-station geometries repeat, occurring somewhat less than 4 minutes earlier each day. Fig. 4 presents the tracking contacts for 1 January 1979. Tracking opportunities for some SV-MS pairs occur 23 hours per day with as many as 12 satellite-station

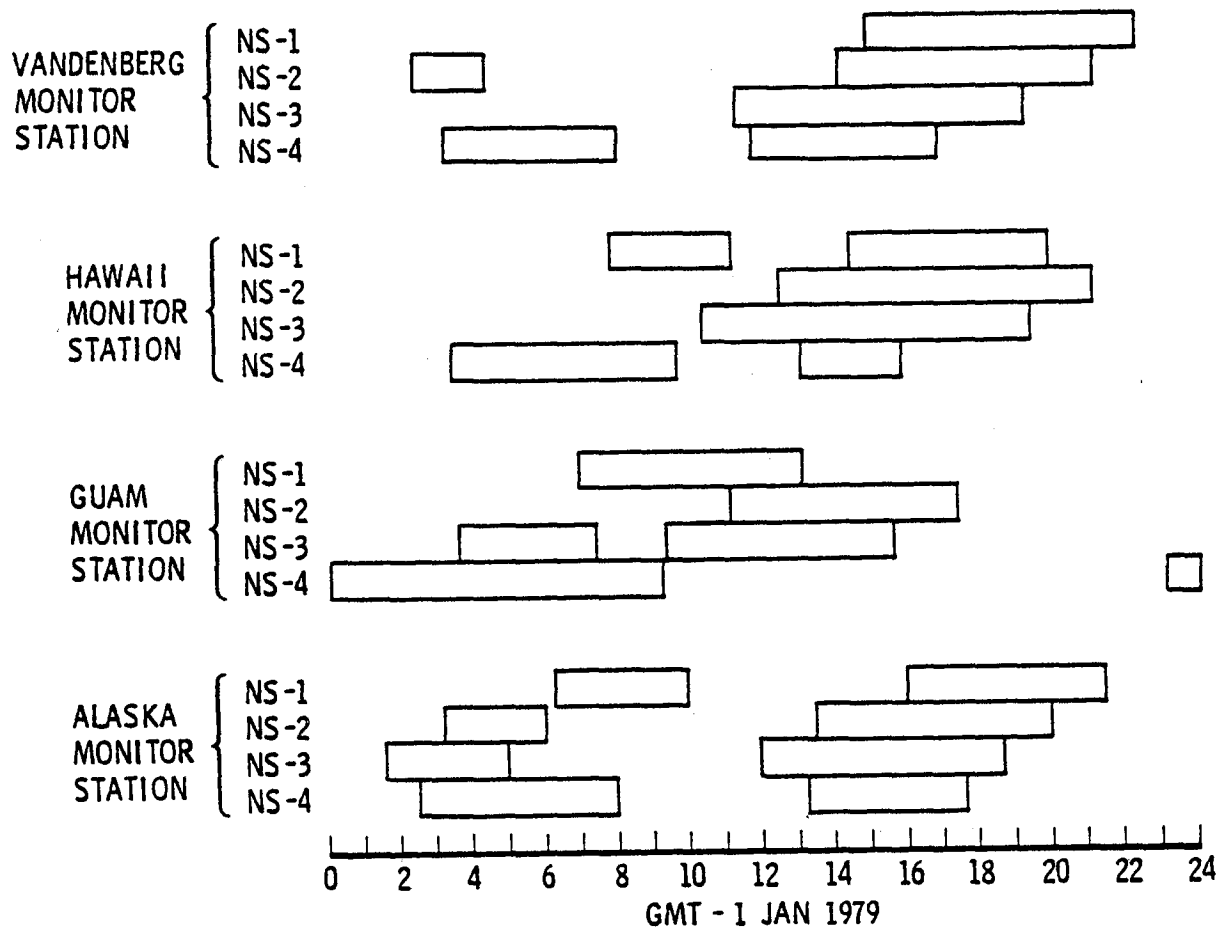


Figure 4. Monitor Station Tracking Schedules

contacts occurring simultaneously, e.g., 1600 GMT. Yuma Proving Ground can be considered to have the same tracking opportunities as Vandenberg monitor station because of their proximity. Thus, the opportunity for four SV tracking at Yuma occurs between 1515 and 1725 GMT on 1 January 1979 where the earlier time is determined by the rise of Navstar 1 while the later time is determined by the fade of Navstar 4. The desirability of incorporating Vandenberg tracking data prior to preparing the upload further reduces the available test window.

### 3. EVALUATION METHODS

Control Segment operations have been supporting Phase I satellites for nearly two years. Much of this time has been used to integrate the system, de-bug hardware and software, and to refine system parameters in order to optimize performance. Sufficient data have been accumulated during the last year to enable the Phase I Control Segment evaluation. Evaluation activities fall into two categories: (1) Master Control Station system performance evaluation and (2) independent validation activity.

#### 3.1 Master Control Station System Performance Evaluation

Within the Master Control Station software is a program for system performance evaluation. This program performs various computational checks and comparisons to monitor Control Segment performance. These checks generally involve comparisons of parameters or functions generated some time in the past with corresponding parameters or functions at current ("real") time. In particular, two computations involving the navigation message have proved useful as a measure of Control Segment performance: (1) measurement residuals and (2) user range error (URE).

##### 3.1.1 Measurement Residuals

Throughout a satellite pass, raw monitor station measurements (pseudo range and delta range) are edited; corrected for such physical phenomena as tropospheric and ionospheric delays, relativity, satellite lever arms, and light transit time delay; and smoothed to yield a current measure of the slant range between the satellite and the monitor station. Using the applicable data block I and II portions of the

navigation message which were last uploaded to the satellite, one can compute the corresponding (predicted) slant range to the satellite. The difference between the smoothed and predicted measurement represents the range error due to the navigation message errors. Fig. 5, is a simplified illustration of the measurement residual computations.

### 3.1.2 User Range Error

The navigation message is prepared and uploaded during the time when the Vandenberg monitor station is tracking. After upload, the satellite is tracked for at least another hour (SV4) and for as much as another five hours (SV2). The newest data represents the best (real time) information on the satellite clock and ephemeris. A predicted pseudo range measurement to a stationary site at Yuma Proving Ground, Arizona is computed from the applicable navigation message (see Fig. 6). A corresponding pseudo range measurement is computed using the current (real time) satellite clock and ephemeris estimates. The difference between these pseudo range computations represents the user range error (URE) attributable to the Control Segment (i.e., navigation message).

### 3.2 INDEPENDENT VALIDATION

In support of the Phase I activities, The Aerospace Corporation has performed independent evaluations of Control Segment performance (see, for example, Reference 3). Evaluation efforts involve post flight ephemeris and clock reconstruction using GPS-supplied data as well as S-band ranging data collected by the Air Force Satellite Control Facility (AFSCF). Also, extensive simulation activity where the truth is precisely known has been used to validate Control Segment performance.

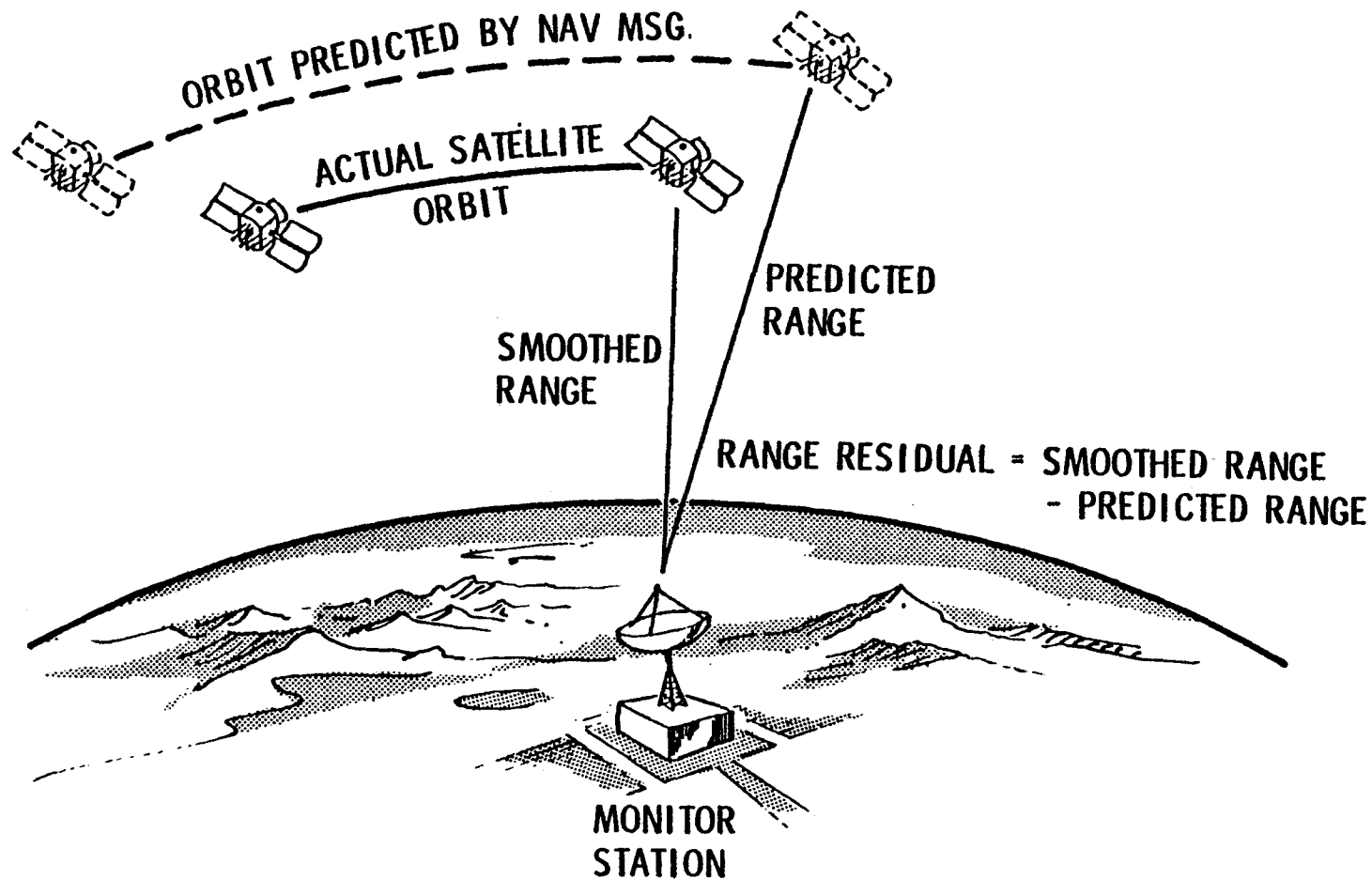


Figure 5. System Performance Evaluation Measurement Residual

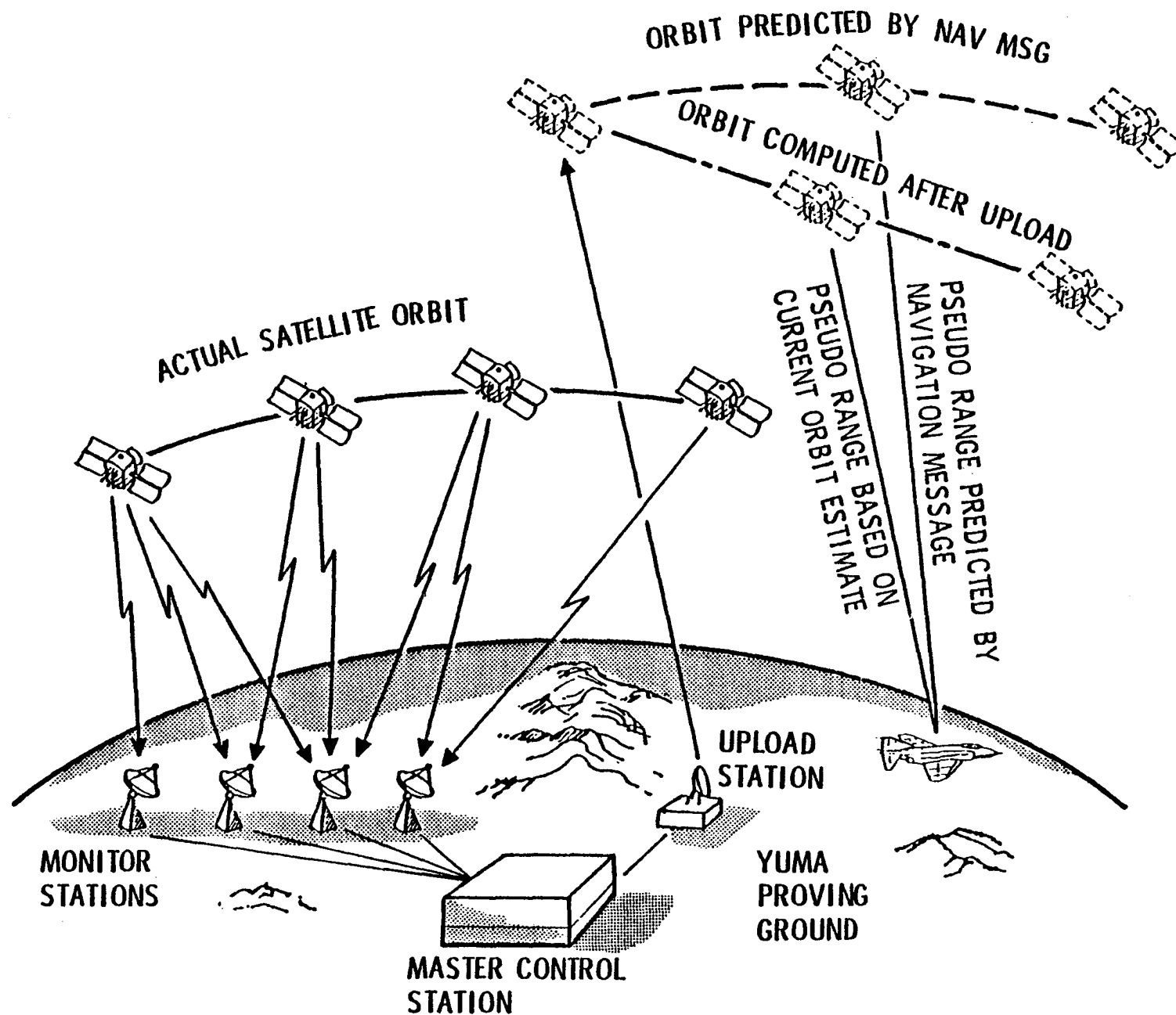


Figure 6. Master Control Station User Range Error Computation



### 3.2.1 Best Fit Ephemeris and Clock

Absolute satellite ephemeris and clock accuracies are difficult to establish. To accomplish post flight reconstruction, a special version of the TRACE program (Ref. 4) has been used to generate best fit ephemeris and clock (BFE/C) estimates. For evaluation purposes, BFE/C estimates are considered to be the closest representations of the "truth" currently available. Three types of data have been used for post flight reconstructions: MCS generated smoothed ranging data (SRTAP), Aerospace generated smoothed ranging data (named APOLY, after the software which generates it) and AFSCF radar ranging data.

#### 3.2.1.1 SRTAP Data

The Master Control Station generates smoothed pseudo range and delta range measurements every fifteen minutes when monitor station tracking data exists. These data referred to as SRTAP data, are the input to the linearized Kalman filter which computes the real time satellite ephemeris corrections and clock states. In addition, this same data is forwarded to the Naval Surface Weapons Center/Dahlgren Laboratories where a reference trajectory for the MCS Kalman filter linearization is generated weekly.

#### 3.2.1.2 APOLY Data

As an alternative to using MCS prepared smoothed data, The Aerospace Corporation has developed a program (named APOLY) which converts raw monitor station (6 second interval measurement) ranging data into smoothed data. Moreover, APOLY uses integrated delta range rather than polynomial generated

range differences to complement the pseudo range data. By doing their own editing, correcting, and smoothing, Aerospace Analysts have absolute control over which data are used and obtain explicit measures of the quality of the data.

#### 3.2.1.3 AFSCF Data

As part of AFSCF support, the GPS satellites are tracked with S-band radars from Satellite Control Facility (SCF) sites extending from the Indian Ocean to northeastern United States. Six daily contacts of 10 minute minimum duration (the Indian Ocean site often gathers as much as one hour), while sparse vis-a-vis GPS tracking densities, provide tracking coverage over more of the orbit than the four GPS monitor station network. The GPS sites stretch only from Guam to Vandenberg AFB.

#### 3.2.1.4 Ephemeris Comparisons

Best Fit Ephemerides (BFE) for the period 16-30 August 1978 were generated: one based on SRTAP data, a second based on APOLY data, and a third based on SCF data. The solution trajectories of each fit were differenced with each other. Agreement between the BFEs was quite good. Figure 7 is an example of the differences between Navstar 2 BFEs using SCF and SRTAP data. Estimated differences in terms of URE are approximately three meters (one sigma). These results are more notable when one considers that Navstar 2 experienced roll momentum dumps on the twentieth and the twenty sixth day of August.

The momentum dumping process was performed with a coupled-pair of 0.1 lb reaction control jets. The location of these jets caused a plume impingement onto the space vehicle,

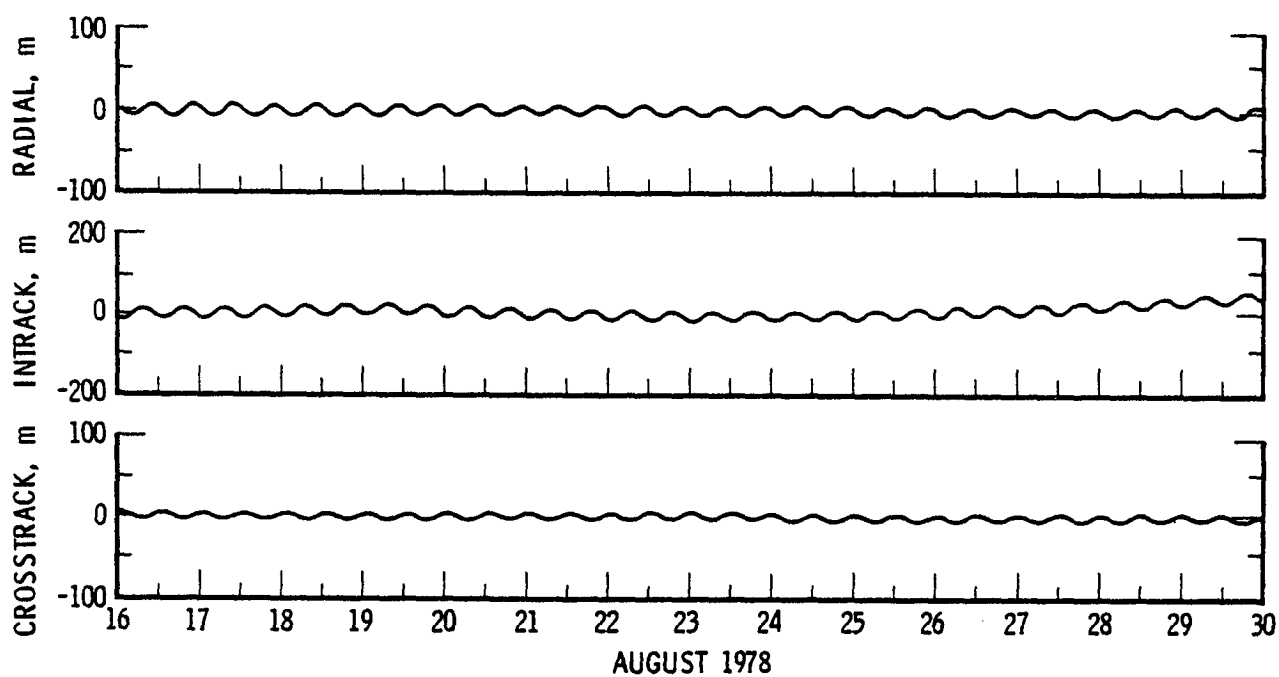


Figure 7. Best Fit Ephemeris Differences for SCF and SRTAP  
Data: Navstar 2 Data for 16-30 Aug 1978

producing an intrack position error of about one hundred meters impulsive per day. A judicious choice of fit parameters to include in-track thrusts in the BFE solutions removed essentially all of the intrack error due to this source.

### 3.2.2 Ephemeris End Around Check

The ephemeris end around check (EEAC) involves a sophisticated simulation of GPS data inputs and outputs (see Ref. 5). Some aspects of the activity are still not completed. When they are, they will be documented. For now, two aspects of EEAC will be useful to this presentation: (1) best fit ephemeris and clock solutions, and (2) monitor station location solutions (geodetic survey). Monitor station survey will be discussed in Para. 4.3. The best fit activity is cited here to demonstrate the efficacy of the post flight reconstruction methodology since in this case the truth is precisely known.

One case (Case 3.X) involved the simulation of two Phase I satellites and four monitor stations. Reference 5 gives specific details of all the simulated effects. Briefly, one satellite was characterized by a cesium frequency standard and Navy's Navigation Technology Satellite II (NTS II) the solar pressure force model, while the second satellite had a rubidium frequency standard and a Navstar solar pressure force model. Force model errors were introduced into the solar pressure and geopotential force models. Other simulated errors included monitor station location coordinates, pole wander values, monitor station clock instabilities based upon ground cesiums, SV random and deterministic clock errors, tropospheric and ionospheric refraction corrections, and white noise on all measurement links.

This data was fit using the same methodology applied to real data. Figures 8 and 9 present the differences between the best fit solutions and the truth. All the error components display the twelve hour periodic structure typical of GPS orbits. Radial errors have amplitudes between one and two meters. Horizontal errors (the root sum square of intrack and crosstrack errors) are approximately fifteen meters for Navstar 1 and ten meters for NTS II. As a result of the altitude of the GPS orbits only between zero (at zenith) and twenty four percent (on the horizon) of the horizontal error maps into the user range error. Hence, the estimated contribution to the user ranging error is about three meters (one sigma).

### 3.3. DATA COLLECTION

Although Control Segment data is collected daily, special data collection periods have been designated for the purpose of performance evaluation. Table III presents a summary of these special periods. The SEG tests (CS-SEG-1) were intended to verify Control Segment performance in support of one, two, and three satellites. Each test was nominally scheduled for four weeks of normal operations. As evidenced in Table III, none of the SEG tests had four consecutive weeks of normal operations. The CS-S-1 (S-1) test was a four satellite full system evaluation. Initially scheduled for 17 January to 13 February, 1979, it was rerun from 26 February to 25 March, 1979. This latter period was devoid of significant anomalies and is considered to be representative of normal operations.

During these test periods extensive data collections were performed and forwarded to General Dynamics/Electronics Division in San Diego, California and The Aerospace Corporation in El Segundo, California for analysis. It is primarily the results of these data analysis activities that are reported in the following section.

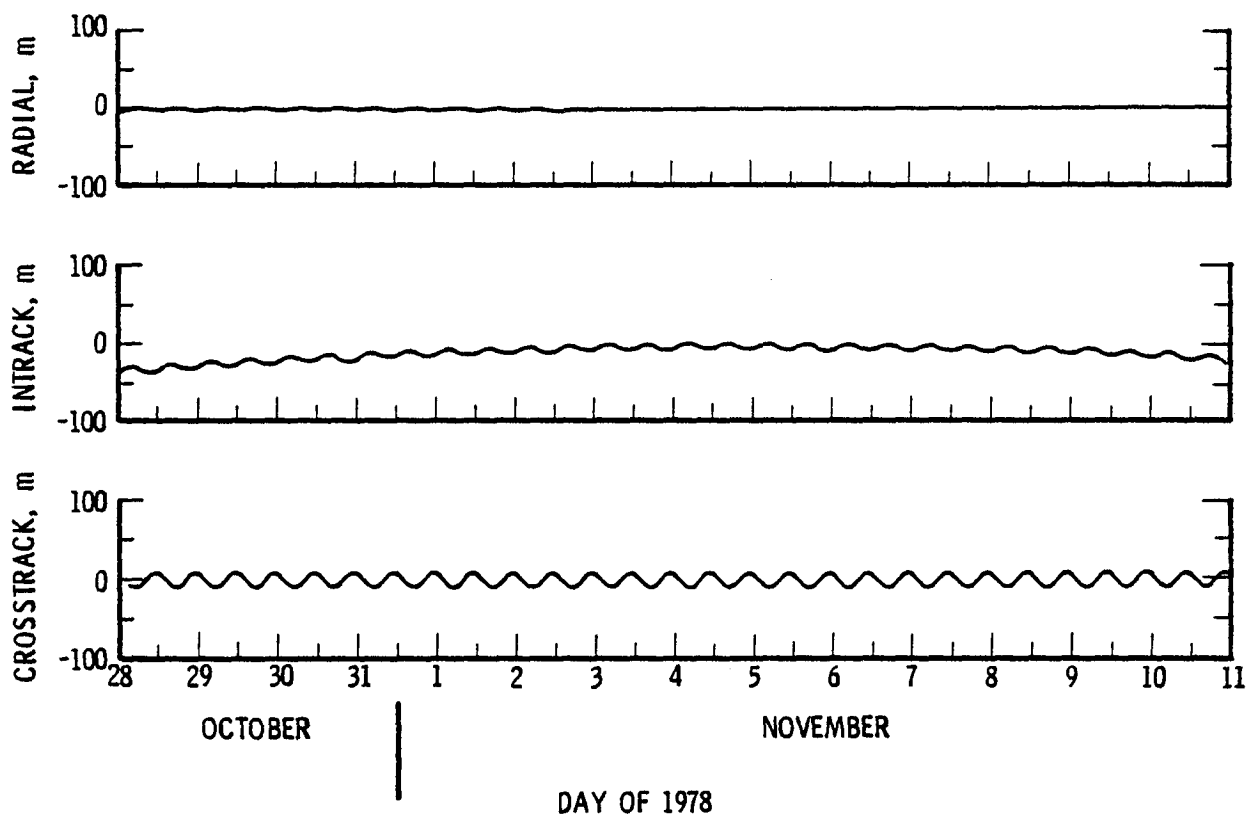


Figure 8 Best Fit Ephemeris Errors for Simulated NTS-II Satellite Data

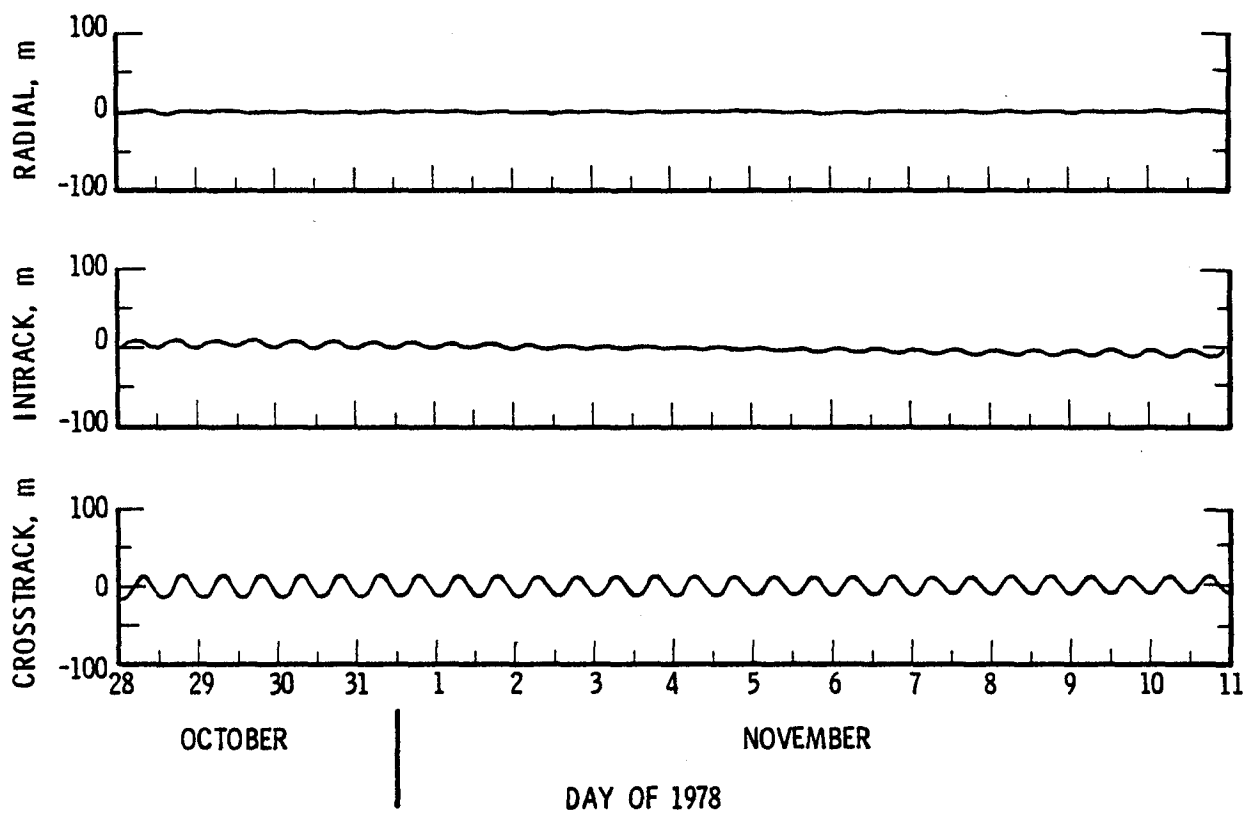


Figure 9. Best Fit Ephemeris Errors for Simulated Navstar 1 Satellite Data

Table III. Special Data Collection Periods

---

TEST	PERIOD
CS-SEG-1 (1 SV)	15 MAY - 12 JUNE 1978
CS-SEG-1 (2 SV)	15 AUG - 12 SEPT 1978
CS-SEG-1 (3 SV)	13 NOV - 20 DEC 1978
CS-S-1 (4 SV)	29 JAN - 23 FEB 1979
	26 FEB - 25 MAR 1979



## 4. RESULTS

This section summarizes Phase I Control Segment performance to date. For more details see Refs 6-9. The results will address the following issues: ephemeris and satellite clock prediction accuracy, i.e., data block I (SV clock) and data block II (ephemeris); almanac accuracy, i.e., data block III.

### 4.1 EPHEMERIS AND SATELLITE CLOCK PREDICTION ACCURACY

#### 4.1.1 Master Control Station System Performance Evaluation

As described in Section 3, this activity is performed with the MCS software. The results reported in Sections 4.1.1.1 and 4.1.1.2 have been supplied by General Dynamics Electronics Division. The remainder of Section 4 is based on analyses performed at The Aerospace Corporation.

##### 4.1.1.1 Measurement Residuals

Satellite positions predicted from the navigation messages are used by the GPS Master Control Station System Performance Evaluation software to compute a predicted range from a given satellite to a Control Segment monitor station currently tracking that satellite. Corrected smoothed pseudo range measurements are then converted into a measured range by subtracting the predicted satellite clock offset and the current estimate of the monitor station clock offset. The difference between these measured and predicted ranges provides a direct indication of the accuracy of the GPS navigation message.

Fig. 10 summarizes the predicted range residuals to the Vandenberg monitor station for the four GPS satellites. The data presented are the root-mean-square (rms) of the predicted range residuals based on data collected during four satellite testing in February 1979. The daily residuals were shifted along the horizontal axis so the data could be evaluated relative to upload time. Note that the residuals for the four SVs before the daily upload are of the order 3-30 meters. At the upload time, the residuals drop towards zero and then begin to disperse. The residuals are not identically zero at upload time because of the timing involved in computing the evaluation parameter. The navigation message is constructed based upon filter estimates at a particular epoch. These data must be uploaded to the satellites and verified by the Control Segment monitor stations before it is available for evaluation. Hence, the message has aged a minimum of fifteen minutes (the nominal Phase I evaluation interval) before measurement data are available for residual formation.

#### 4.1.1.2 User Range Error

Section 3.1.2 described the URE computation performed by the MCS System Performance Evaluation. The CS-S-1 test performed from 26 February through 25 March 1979 was a period of stable GPS operation. Daily URE data were accumulated for the four satellites. The root-mean-square (rms) of these URE values are plotted in Fig. 11 as a function of time since the navigation message was uploaded to the satellite. It should be added that the mean value of the URE for each satellite is less than 1.5 meters; hence the rms value can also be interpreted as the standard deviation with no significant error.

As a consequence of the satellite geometries (see Section 2), Navstar 4 is visible to Yuma for less than 2 hours

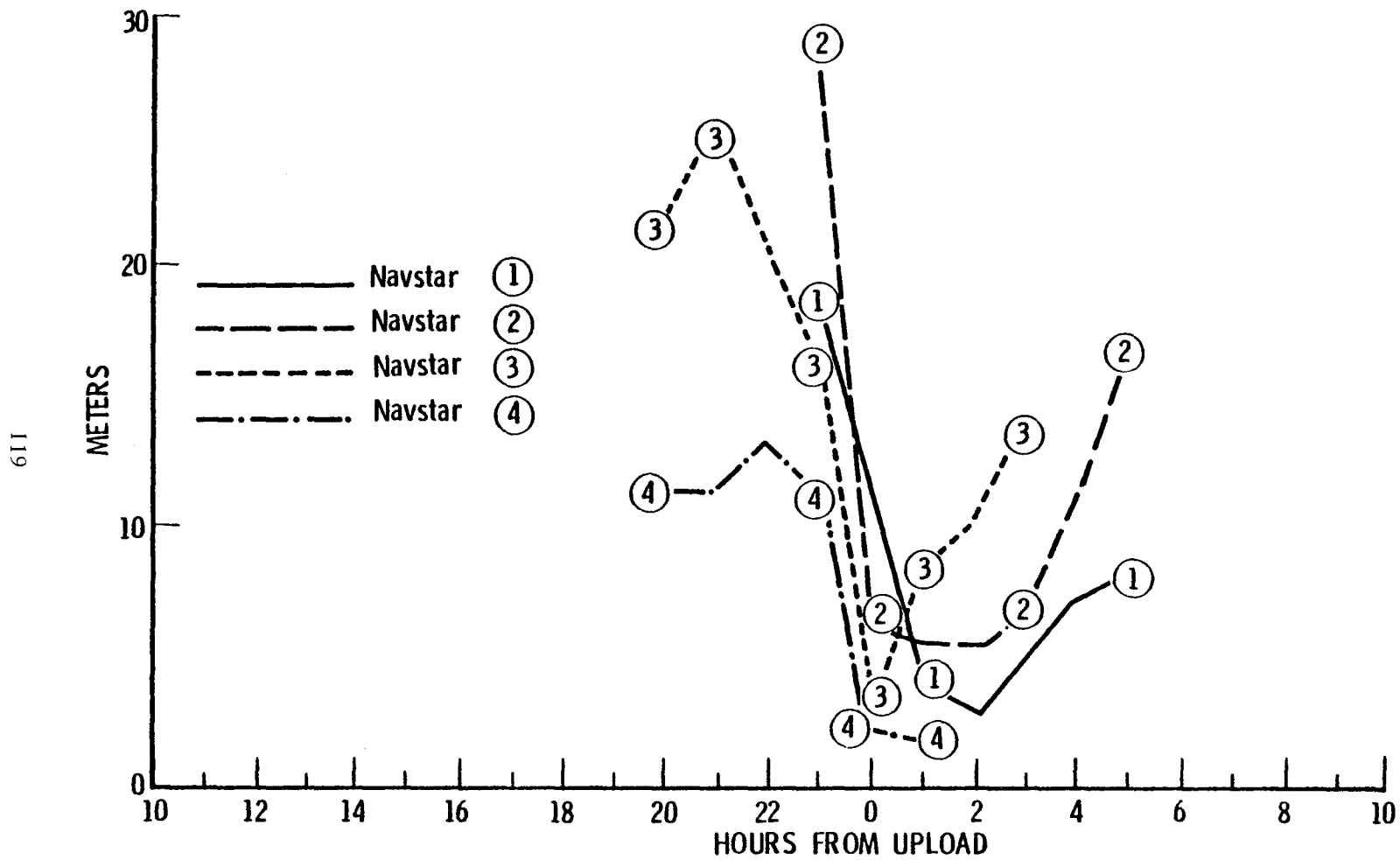


Figure 10. RMS of Predicted Range Residuals at Vandenberg

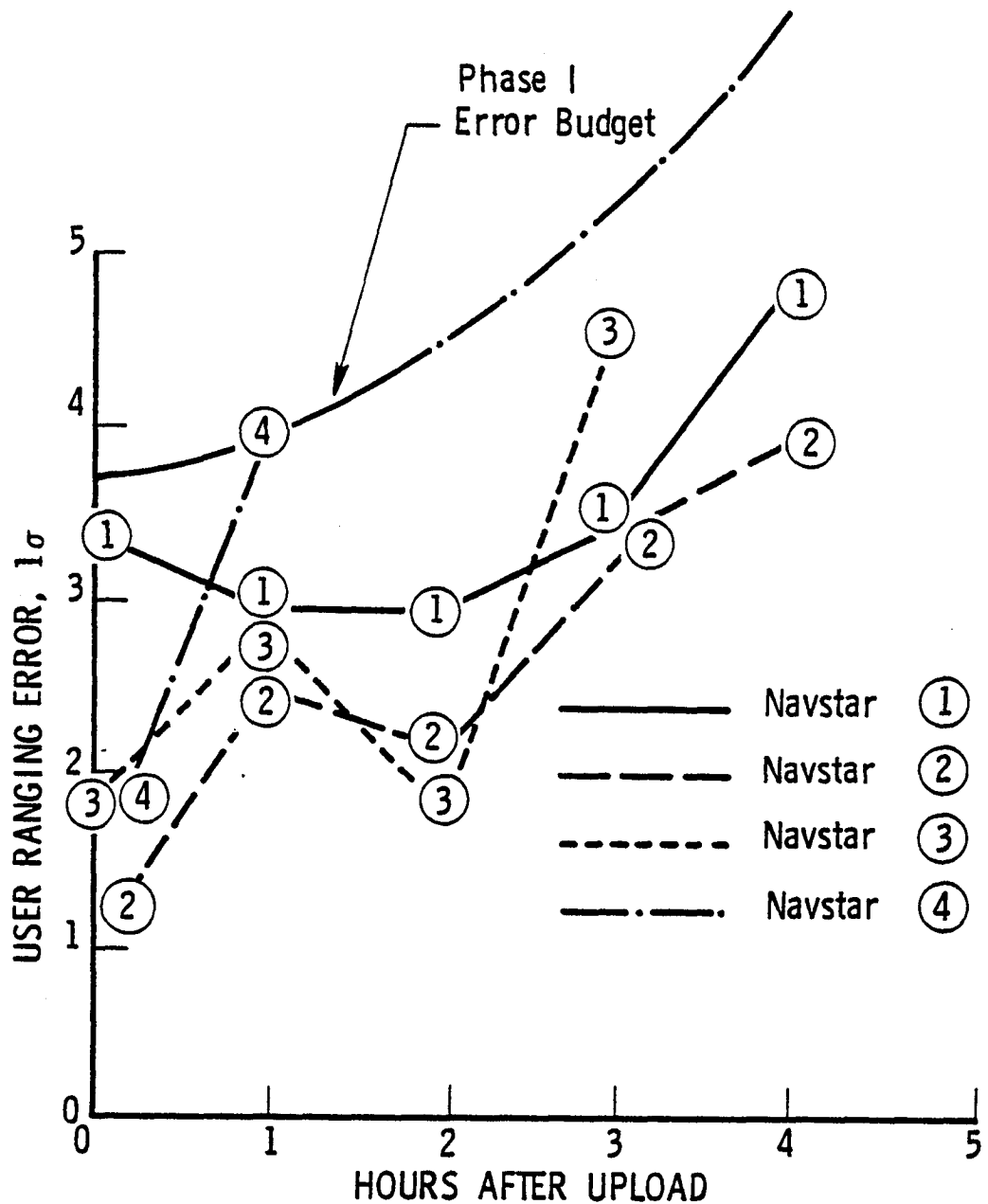


Figure 11. User Ranging Error Based on MCS System Performance Evaluation

after the fourth satellite (Navstar 2) rises. During the first two hours after upload Navstars 1, 2, and 3 better the required accuracy by more than one meter. Although Navstar 4 exceeds the one hour error budget by 0.1 meters (4.0 vs 3.9 meters), the difference is quite small. In general, all four satellites better the Phase I accuracy requirements during the entire period they are visible to Yuma after upload.

#### 4.1.2 Independent Validation

The twenty-six navigation messages broadcast by the satellite (one message each hour) predict the position and SV clock offset around the entire orbit, actually extending two hours into the next day. These predictions have been compared against the "truth" solution (BFE/C) prepared by The Aerospace Corporation (see Section 3.2) during the special data collection periods. Figures 12 and 13 present the Navstar 1 and 2 ephemeris and clock errors as determined from the upload messages on 16 Aug 1978 (day 228). The small data loss in the first hour is due to the MCS computation lag between the time the navigation message is prepared and the time it is uploaded, verified, and then broadcast. During this time the satellite is broadcasting the navigation message uploaded previously.

Radial and crosstrack ephemeris errors have a characteristic twelve hour periodicity. Intrack errors, while also of twelve hour periodicity, have a secular error growth in addition. Clock errors, on the other hand, should look more like a random walk. However, the clock errors on 16 August show some periodic characteristics. This appears to be a result of (1) relative paucity of data due to unavailability of Guam tracking station, (2) induced correlations between clock state and ephemeris state estimates due to high altitude (4.2 earth radii) of GPS orbits, and (3) induced correlations due to best fit clock processing.

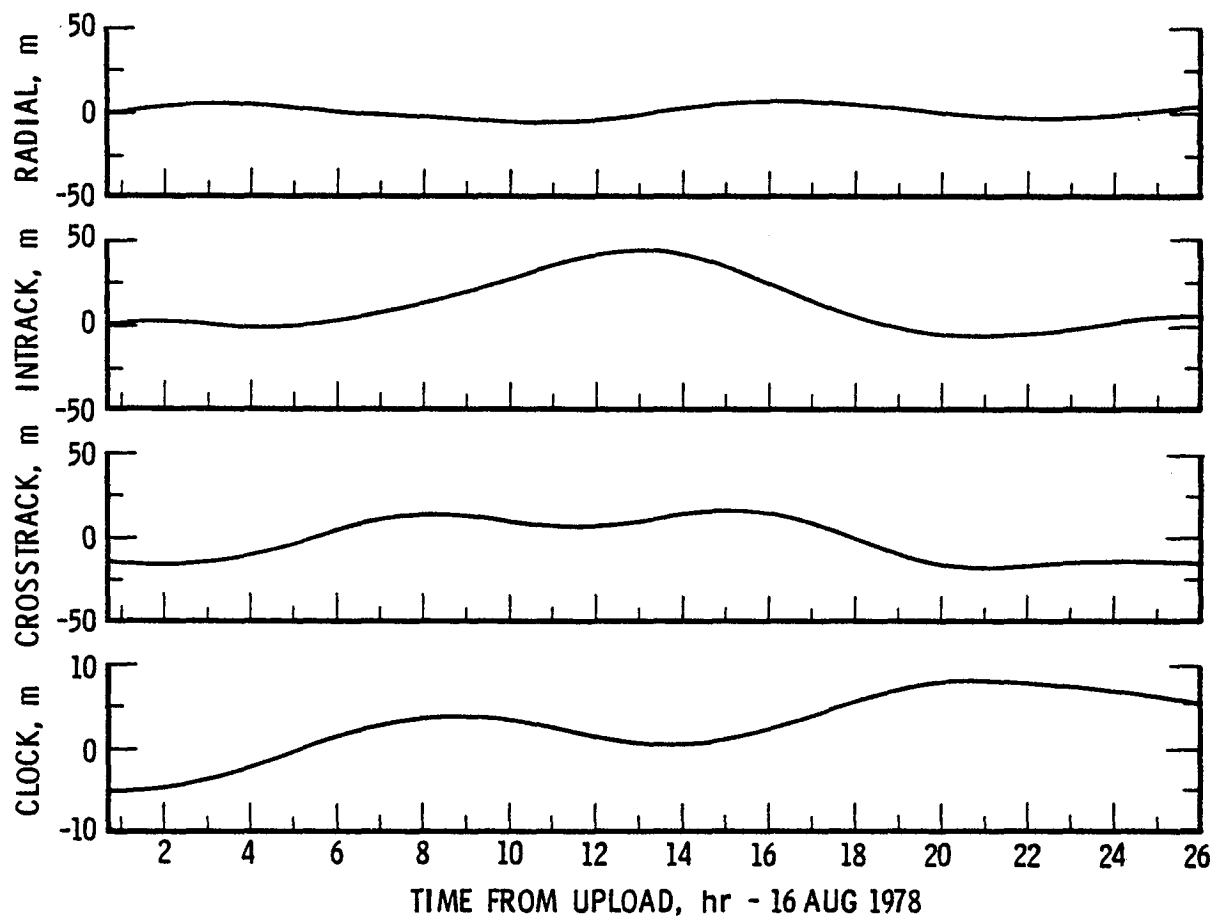


Figure 12. Navstar 1 Ephemeris and Clock Prediction Errors for 16 Aug 1978

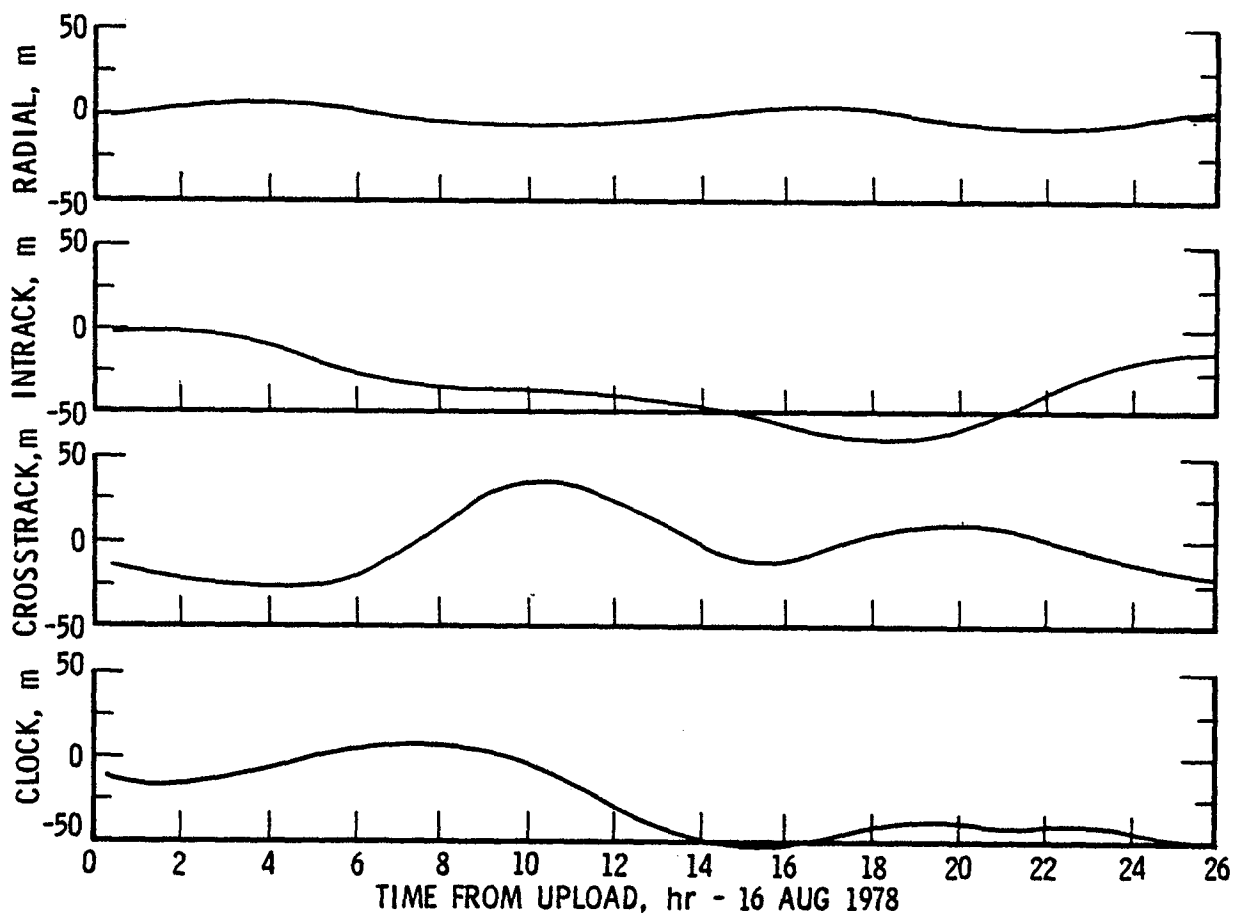


Figure 13. Navstar 2 Ephemeris and Clock Prediction Errors for 16 Aug 1978

Next, the ephemeris and clock errors are converted to user ranging errors by mapping the contributions onto the line-of-sight to (fictional) uniformly distributed users on the earth's surface. At each time point, the range errors for the uniformly distributed user population are computed and the corresponding statistics are tabulated. Fig. 14 presents the 68 percent error curves for Navstars 1 and 2 for 16 Aug 1978. To interpret this result, remember that 68 percent of all users who can see the satellite (masking angle is five degrees for these computations) will incur errors equal to or less than the value indicated by the curve. On 16 Aug, the maximum global user range error was 10 meters during the first two hours and about 22 meters during the twenty four hour period after upload.

#### 4.1.2.1 Two Vehicle Testing

A similar activity was done for each day during which an upload was generated during the CS-SEG-1 (2 SV) test period. A total of 10 days between 16 and 31 August had acceptable uploads (weekends were excluded, and two days had some difficulties). Cumulative error statistics for the two-week test period are presented in Fig. 15. Two curves - one for the first two hour period after the upload message was generated and the second for the twenty-four hour period after the upload message was generated - summarize the Control Segment ephemeris and SV clock prediction performance. To interpret the figure, given a point on either curve  $x_1$  = URE,  $y_1$  = probability), one states that for the indicated time span (i.e., 0-2 hours or 0-24 hours) there is a probability of  $y_1$ , that a user will incur a URE less than or equal to  $x_1$ . Ergo, there is a 68 percent probability that the user ranging error is less than 6.5 meters during the first two hours after upload. While this value is almost two meters beyond the error budget it is a very positive result when one considers that at this point in time:



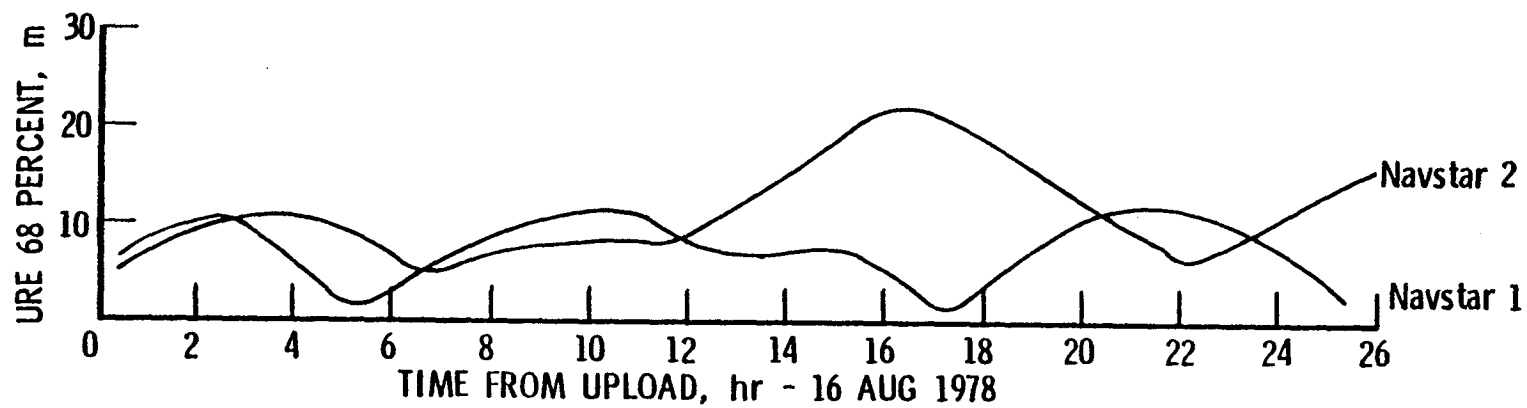


Figure 14. Global User Range Error Statistics

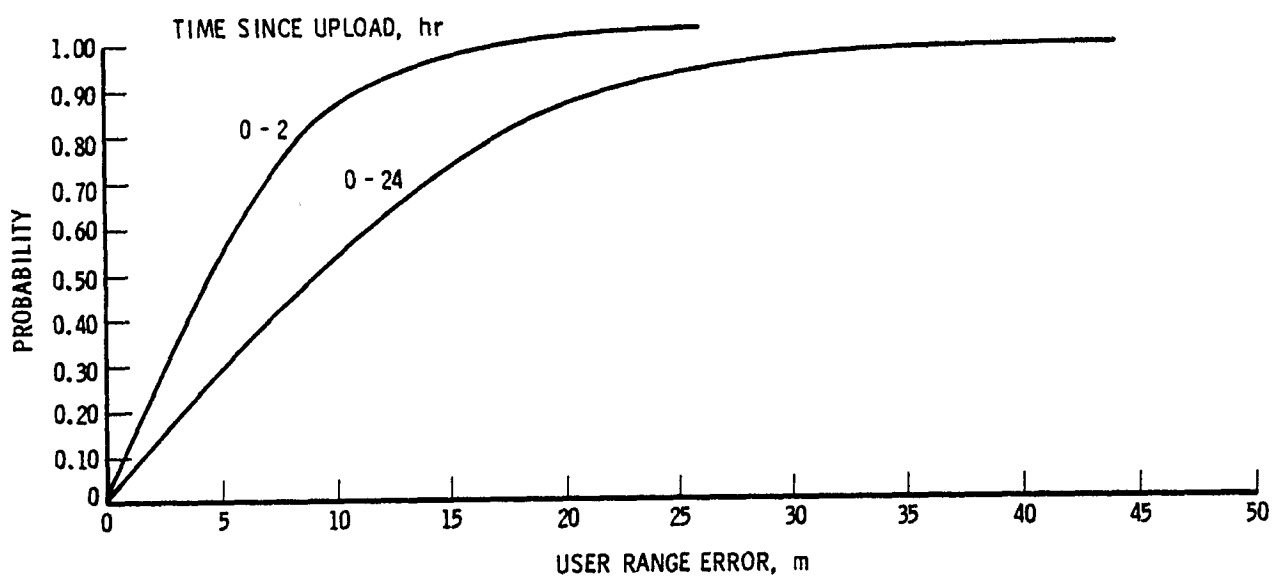


Figure 15. Cumulative Error Distribution From Ephemeris and SV Clock for All Satellites

- Navstar 2 incurred intrack velocity impulses during the attitude control system roll momentum dumping process. This phenomenon was caused by plume impingement during the firing of the 0.1 lb reaction control thrusters. The momentum dump impingement anomaly was identified during the BFE processing - a month or more after the test period.
- The Control Segment software was still in a state of checkout. Several corrections have since been made - primarily in the data base.

The twenty-four hour URE statistics are impressive when one realizes that the SV rubidium clock should contribute nearly 37 meter (1 sigma) to the URE. According to the curve, for the 16-31 Aug. time period, the 68 percent probability yields a URE of 14 meters - which includes ephemeris and clock.

#### 4.1.2.2 Three Vehicle Testing

A similar exercise was performed for the CS-SEG-1 (3 vehicle) test period. Seventeen days in the period 14 November to 8 December had uploads included in the cumulative error statistics shown in Figure 16. Again, two curves are used to summarize the Control Segment ephemeris and SV clock prediction performance; the first depicts performance for the first two hours after an upload while the second is for the twenty four hour period after the upload.

A procedural change strongly affected the character of these results. In an attempt to obtain ephemerides independent of GPS data, the previously referenced tracking data from the Air Force Satellite Control Facility was used as the basis for generating the BFE used in this comparison. This data was not corrected for ionospheric propagation effects at all, and was corrected for tropospheric propagation effects by use of a procedure different from that used at the MCS. While the

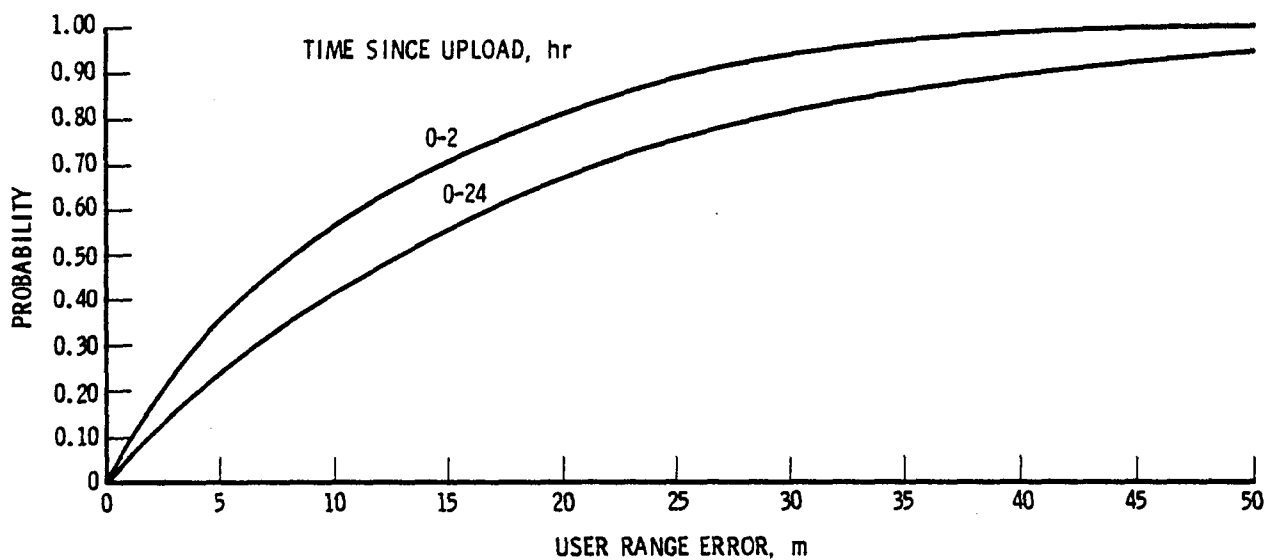


Figure 16. Cumulative Error Distribution From Ephemeris and SV Clock for All Satellites - Three Vehicle Test

long-arc fits to these AFSCF data appeared of acceptable quality, it was subsequently demonstrated that their predict performance was noticeably poorer than those obtained from GPS-obtained data. This poorer predictive capability is sharply evident in these three satellite test results.

Additional problems hampered these analyses;

- A different clock was employed on Navstar 2 during this test than was used on the 2 vehicle test. This clock exhibited a 56 sec-period oscillation throughout this test. Additionally, this clock at that time manifested some as yet unexplained frequency excursions typically of many minutes duration and of several tens of meters' magnitude in pseudo range. These factors have led to worsening of Navstar's prediction performance by a factor of 2 or more.
- Guam monitor station was not operational
- Navstar 2 had a 56 second period anomalous oscillation in the 1575.42 Mhz carrier signal with amplitude 50 times greater than expected
- Navstar 1 had emerged from its eclipse season just prior to the 3 vehicle test span. It has been observed throughout these analyses that orbit and clock prediction are relatively worse in and near eclipse seasons than between eclipse seasons.
- Plume impingement during roll momentum dump firings was again a problem during this test. If anything, the number of momentum dumps was larger in this interval than during the two vehicle test.

#### 4.1.2.3 Four Vehicle Testing

Four vehicle data for the period 29 January - 12 February 1979 was employed to examine the predictive capabilities of that configuration. Ten days of valid uploads are included in this sample. Cumulative error statistics are given in Figure 17, as before, in the four vehicle 2 hour and 24 hour prediction curves.

These data were reduced using a GPS data based BFE Predict Performance characteristics of this configuration and seen to be smaller than the two vehicle data presented earlier. The two hour value of less than 5.5 in with a 68 percent probability is closer to the specification error budget than previously reported values. In this two week interval there were two cases of anomalous clock performance, and the previously noted 56 second oscillation on Navstar 2's clock continued to plague the analysis. However, by the use of the magnetic torque momentum control system the incidence of thrusting to control momentum was eliminated. A change in the MCS data case process noise values resulted in more accurate predictions during this period, as is shown in Figure 17.

Table IV summarizes the 68% values for each of the three described here. It presents data by Navstar vehicle as well as points from the composite curves, Figures 15-17. The specific problems addressed earlier are clearly reflected in the summary.

The four vehicles analyzed here were part of a preliminary examination of four vehicle test results. Both the individual Navstar SV results and the composite are very encouraging as steps toward meeting the specification of 5 meters in 2 hours, 68% of the time. A preliminary look at the

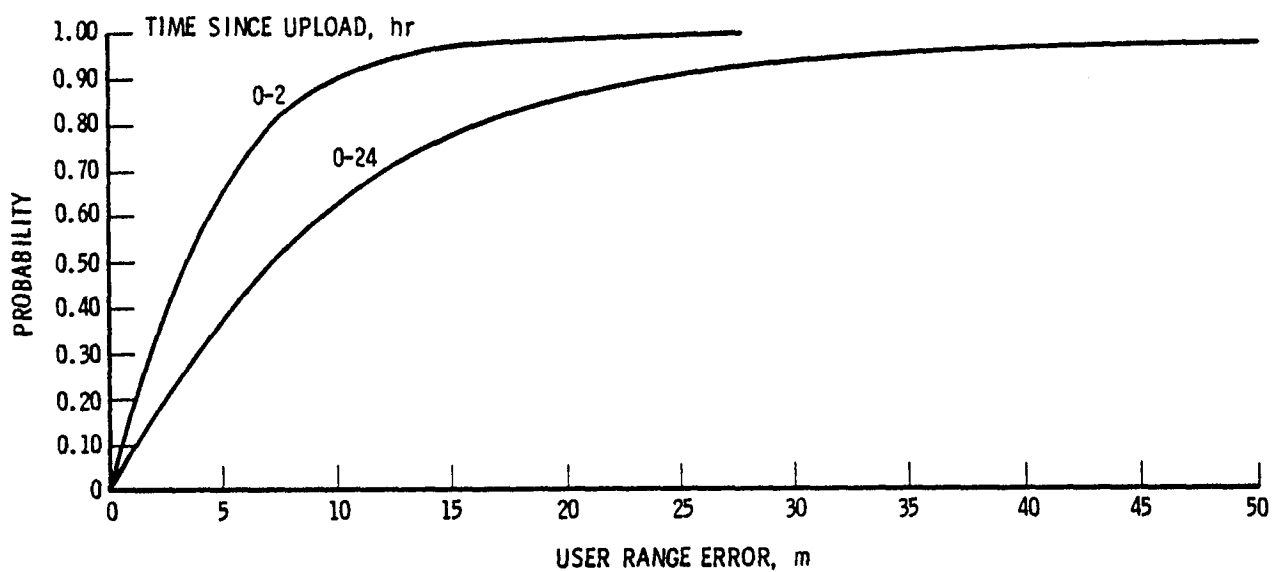


Figure 17. Cumulative Error Distribution From Ephemeris And SV Clock for All Satellites - Four Vehicles

Table IV. Test Summaries

Two Vehicle Cumulative Summary

	<u>NAV 1</u>	<u>NAV 2</u>	<u>ALL (B Chart)</u>
68%, 0-2	7.3m	5.5m	6.5m
68%, 0-24	14.1m	12.4m	14 m

Three Vehicle Cumulative Summary

	<u>NAV 1</u>	<u>NAV 2</u>	<u>NAV 3</u>	<u>ALL</u>
68%, 0-2	13.5m	12 m	10 m	13.5m
68%, 0-24	23.5m	29 m	12 m	20.5m

Four Vehicle Cumulative Summary

	<u>NAV 1</u>	<u>NAV 2</u>	<u>NAV 3</u>	<u>NAV 4</u>	<u>ALL</u>
68%, 0-2	5 m	6 m	4 m	7.5m	5.5m
68%, 0-24	11.5m	27 m	12 m	6 m	11.5m

CS-S-1 (see Table III) data indicates it is of higher quality and more nearly free of annoying anomalies. It is anticipated that all vehicles will meet specification value during this period.

Of special interest are the 24 hour predict values, which are much better than had been anticipated from analyses assuming a 1 part in  $10^{12}$  fractional frequency stability clock.



## 4.2 ALMANAC EVALUATION

The methodology for evaluating the almanac (data block III) message is quite similar to that used for the independent validation of the ephemeris and SV clock messages (see section 4.1.2). Data block III has only one message per satellite per day. Moreover, it is intended to be useful (to much less accuracy) over extended time periods (see Table I). Thus, in evaluating almanac messages, the time scale is in days rather than hours. Here, as in section 4.1.2, the evaluation is based on data collected from 16 to 31 August 1978.

Fig. 18 presents the results of the almanac evaluation for messages generated during the CS-SEG-1 (2 SV) test. These messages spanned the period 16 to 31 August. If the one sigma values of Table I are interpreted as 68 percent probable URE, the almanac accuracies during the 2 SV SEG test appear to satisfy the error budget over the five week evaluation interval.

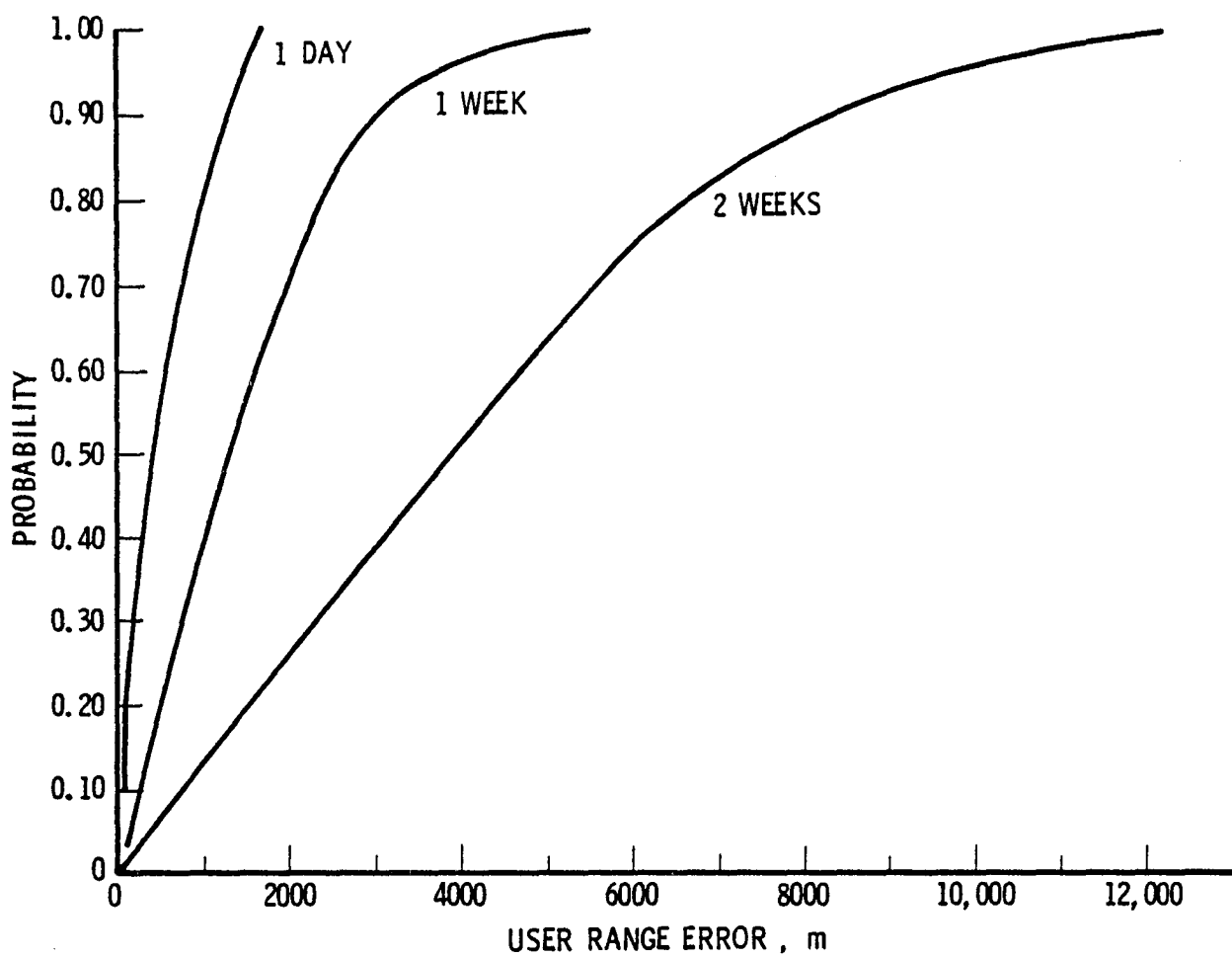


Figure 18. Cumulative Error Distribution for Almanac Message

## 5. CONCLUSIONS

Control Segment test evaluations have occurred during Spring 1978 (1 SV), Summer 1978 (2 SV), Fall 1978 (3 SV), and Winter 1979 (4 SV). The one SV test period was of little value because of many anomalous conditions. The two SV test period during Summer 1978 had two weeks' usable data. The three SV test period had over three weeks of usable data. Two weeks of 4 vehicle tracking were examined as a preliminary look at the formal four vehicle test data. Analysis on these periods forms the basis of this paper.

GPS system checkouts were still occurring in summer 1978. The evolution of Monitor Stations capability and reliability has increased continually from that period to the present. Plume impingement during momentum wheel unloading, which were causing in-track satellite perturbation approaching 100 meters a day, were identified in the course of these analyses. This problem has been removed through the use of magnetic torque for momentum wheel unloading. The checkout operations included a large number of problems solved, anomalies identified, fixes devised, work-arounds installed, and general systems development. Throughout it all, (perhaps despite it all), the Control Segment continued to perform its functions extremely well. Specifically:

- Control Segment user ranging error contributions were only about 1 meter over the specified values (i.e., 5.5 meters vice 4.6 meters) for the two hour period following upload.
- Twenty-four hour URE values were below what was anticipated from the Phase I rubidium SV clocks.
- Almanac accuracy met the URE budget.

## 6. REFERENCES

- (1) System Specification for The Navstar Global Positioning System, SS-GPS-101B, 15 April 1974.
- (2) Space Vehicle Navigation Subsystem and NTS PRN Navigation Assembly/User System Segment and Monitor Station Interface Control Document, MH08-00002-400, Revision F, 13 April 1977.
- (3) H. Bernstein, Global Positioning System (GPS) Phase I Accuracy Analysis Concept, Report No. TOR-0076(6474-01)-3, The Aerospace Corporation, El Segundo, California, 25 July 1975.
- (4) R. H. Prislin, and D. C. Walker, TRACE 66 Trajectory Analysis and Orbit Determination Program, Report No. TR-0059(9320)-1, Vol. I, The Aerospace Corporation, El Segundo, California, 15 August 1971.
- (5) D. A. Conrad, Data Base for GPS Ephemeris End Around Check, TOR-0079(4473-04)-3, 1 April 1979.
- (6) Post Launch CS/SV Test, CS-SEG-1 Category II Final Test Report, Revision B, 11 December 1978
- (7) Post Launch CS/SV Test, CS-SEG-1 (2 SV), Category II Final Test Report, Revision B, 5 March 1979
- (8) Post Launch CS/SV Test, CS-SEG-1 (3 SV) Category II Final Test Report, 30 March 1979 (Draft).
- (9) Post Launch CS/SV Test, CS-S-1, Category II Final Test Report, To Be Delivered